11 Nonunions of the Femoral Shaft and Distal Femur

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INTRODUCTION AQ1

Nonunion following a femur fracture is relatively uncommon. The rate of nonunion following intramedullary nail fixation for a femur fracture is generally believed to be 2% or less (1–3). Although most femur fractures heal uneventfully, those that progress to nonunion tend to be stubborn. Healing the bone presents the primary clinical challenge (4). Soft tissue problems are infrequent in femoral nonunions due to the nature of the thigh musculature.

Various treatment options have been described to treat these challenging problems. Table 1 reviews the available literature on femoral nonunions by treatment, anatomic location, subgroup (uninfected, infected, and segmental defect), and most recent failed treatment. T1

CLINICAL EVALUATION

The clinical evaluation consists of the patient history and physical examination. The patient history should include the date and mechanism of the initial injury as well as any preinjury medical problems (diabetes, malnutrition, metabolic bone disease, etc.), disabilities, or associated injuries that might affect the treatment plan or outcome. All prior surgeries to treat the fracture and fracture nonunion should be reviewed. The history should also include details regarding infection. Finally, the patient should be questioned regarding other possible contributing factors for nonunion. Any current use of nonsteroidal anti-inflammatory drugs (NSAIDs) should be discontinued.

The physical examination is used to document the current status of the affected limb and the functional status of the patient. The nonunion site and the hip and knee joints should undergo manual testing to evaluate motion, pain, and stability. The presence of active drainage and sinus formation should be noted. The presence of deformity at the fracture site should be noted and described. A neurovascular examination should be performed to rule out or document vascular insufficiency and motor or sensory dysfunction.

RADIOLOGIC EVALUATION

The radiologic evaluation begins with a review of the original fracture films and subsequent radiographs of the salient aspects of previous treatments. This review allows evaluation of the character and severity of the initial injury and of the progress or lack of progress toward healing. The prior plain films should be carefully examined for the status of any orthopedic hardware (e.g., loose, broken, inadequate in size, or number of implants) including its removal or insertion on subsequent films. The evolution of deformity at the nonunion site over time should be evaluated. The time course of missing or removed bony fragments, bone grafting, and implanted bone stimulators allows for an assessment of the associated fracture repair response.

Current radiographs should be taken and should include (i) a 36 in anteroposterior (AP) and lateral radiograph of the entire femur, including the hip and knee joint; (52) AP, lateral, AQ2

Table 1 Literature Review of Femoral Nonunions

Anatomic location	Subgroup	Most recent failed treatment	Authors	Treatment (number of cases)	Success rate	Time to bony union	Adjunctive treatments
Subtrochanteric	Uninfected	Intramedullary nail	Haidukewych and Berry (5)	Exchange nailing (11 cases)	100%	Not reported	Cancellous autograft or allograft or both (number of cases not reported)
		Plate and screw fixation	Haidukewych and Berry (5)	Repeat plate and screw fixation (8 cases)	88%	Not reported	Cancellous autograft or allograft or both (number of cases not reported)
			Charnley and Ward (6)	Intramedullary nail (2 cases)	100%	5 mo	None
			Kempf et al. (7)	Intramedullary nail (7 cases)	86%	4 mo	None
			Haidukewych and Berry (5)	Intramedullary nail (4 cases)	100%	Not reported	Cancellous autograft or allograft or both (number of cases not reported)
Diaphyseal	Uninfected	Intramedullary nail	Bungaro et al. (8)	Plate and screw fixation (7 cases)	100%	Not reported	Autologous cancellous bone grafting (all cases)
			Bai et al. (9)	Plate and screw fixation (6 cases)	83%	6 mo	Composite graft of bovine BMP and plaster (all cases)
			Wu and Shih (10)	Plate and screw fixation (14 cases)	79%	5 mo	Autologous cancellous bone grafting (13 cases)
			Bellabarba et al. (11)	Plate and screw fixation (23 cases)	91%	3 mo	Autologous cancellous bone grafting (13 cases)
			Cove et al. (12)	Plate and screw fixation (8 cases)	100%	6 mo	Autogenous bone grafting (all cases)
			Ueng et al. (13)	Augmentative plating (10 cases)	100%	8 mo	None
			Ueng and Shih (14)	Augmentative plating (5 cases)	100%	5 mo	Cancellous bone grafting (3 cases)
			Pihlajamaki et al. (15)	Exchange nailing (11 cases)	64%	10 mo	Autogenous bone graft (3 cases)
			Wu and Chen (16)	Exchange nailing (36 cases)	92%	4 mo	None
			Wu and Shih (10)	Exchange nailing (32 cases)	81%	4 mo	Autologous cancellous bone grafting (9 cases)
			Heiple et al. (17)	Exchange nailing (5 cases)	96%	4 mo	None
			Christensen (18)	Exchange nailing (8 cases)	100%	Not reported	None
			Cove et al. (12)	Exchange nailing (2 cases)	100%	8 mo	Autogenous bone grafting (1 case)
			Furlong et al. (19)	Exchange nailing (25 cases)	96%	7 mo	Autogenous bone grafting (12 cases)
			Kempf et al. (7)	Exchange nailing (6 cases)	83%	4 mo	None
			Hak et al. (20)	Exchange nailing (18 cases)	72%	Not reported	None
			Harper (21)	Exchange nailing (8 cases)	75%	7 mo	Autogenous bone grafting (5 cases)
			Oh et al. (22)	Exchange nailing (11 cases)	100%	Not reported	None
			Wu et al. (23)	Exchange nailing (45 cases)	96%	4 mo	Corticocancellous bone grafting and

					acute lengthening (all cases)
	Wu and Chen (24)	Exchange nailing (16 cases)	100%	4 mo	None
	Weresh et al. (25)	Exchange nailing (19 cases)	53%	8 mo	None
	Finkemeier and Chapman (26)	Exchange nailing (28 cases)	68%	11 mo	Autogenous bone grafting (11 cases)
	Pihlajamaki et al. (15)	Nail dynamization (19 cases)	74%	5 mo	Autogenous bone graft (2 cases)
	Menon et al. (27)	Slow compression over a nail using external fixation (SCONE)(2 cases)	100%	8 mo	None
	Brinker and O'Connor (28)	SCONE (3 cases)	100%	4 mo	None
	Wu and Chen (24)	Open autogenous bone grafting (19 cases)	100%	5 mo	None
	Pihlajamaki et al. (15)	Autogenous bone grafting (5 cases)	0%	Not applicable	None
Plate and screw fixation	Bai et al. (9)	Repeat plate and screw fixation (4 cases)	100%	6 mo	Composite graft of bovine BMP and plaster (all cases)
	Cove et al. (12)	Repeat plate and screw fixation (12 cases)	100%	8 mo	Autogenous bone grafting (10 cases), allograft (2 cases)
	Wu et al. (29)	Intramedullary nail (8 cases)	88%	4 mo	Autologous corticocancellous bone grafting (all cases)
	Wu et al. (30)	Intramedullary nail (21 cases)	100%	5 mo	Reaming bone grafting (all cases)
	Bai et al. (9)	Intramedullary nail (5 cases)	100%	6 mo	Composite graft of bovine BMP and plaster (all cases)
	Wu and Shih (10)	Intramedullary nail (29 cases)	86%	4 mo	Autologous cancellous bone grafting (14 cases)
	Heiple et al. (17)	Intramedullary nail (4 cases)	100%	4 mo	None
	Christensen (18)	Intramedullary nail (4 cases)	100%	Not reported	None
	Kempf et al. (7)	Intramedullary nail (8 cases)	100%	4 mo	Autogenous cancellous bone grafting (4 cases)
	Harper (21)	Intramedullary nail (3 cases)	100%	4 mo	Autogenous bone grafting (2 cases)
	Wu et al. (23)	Intramedullary nail (6 cases)	83%	3 mo	Corticocancellous bone grafting; acute lengthening (all cases)
Traction and casting	Heiple et al. (17)	Intramedullary nail (16 cases)	94%	4 mo	None
	Wu and Shih (10)	Intramedullary nail (4 cases)	75%	5 mo	Autologous cancellous bone grafting (1 case)
	Christensen (18)	Intramedullary nail (5 cases)	100%	Not reported	None

(*Continued*)

Table 1 Literature Review of Femoral Nonunions (*Continued*)

Anatomic location	Subgroup	Most recent failed treatment	Authors	Treatment (number of cases)	Success rate	Time to bony union	Adjunctive treatments
			Harper (21)	Intramedullary nail (5 cases)	80%	8 mo	Autogenous bone grafting (4 cases)
Diaphyseal	Infected	Intramedullary nail	Klemm (31)	Exchange nailing (16 cases)	100%	Not reported	Internal irrigation after nail placement; irrigation, and debridement after nail removal following consolidation (all cases)
			Christensen (18)	Exchange nailing (3 cases)	100%	Not reported	None
			Hak et al. (20)	Exchange nailing (5 cases)	100%	Not reported	None
			Oh et al. (22)	Exchange nailing (2 cases)	100%	Not reported	None
			Kostuik and Harrington (32)	Incision and drainage, retained nail (10 cases)	40%	18 mo	None
			Cove et al. (12)	Serial debridements followed by plate and screw fixation (3 cases)	100%	18 mo	Vascularized fibular transfer and autogenous bone grafting (all cases)
			Barquet et al. (33)	Serial debridements followed by external fixation (6 cases)	83%	9 mo	Cancellous bone grafting (all cases)
			Slätis and Paavolainen (34)	Debridement and external fixation (2 cases)	100%	5 mo	Cancellous bone grafting (all cases)
			Ueng et al. (35)	Debridement followed by external fixation (9 cases)	100%	8 mo	Antibiotic-eluting beads for 2 to 6 wk and cancellous bone grafting (6 cases), and vascularized fibular transfer (3 cases)
		Plate and screw fixation	Klemm (31)	Intramedullary nailing (21 cases)	86%	Not reported	Internal irrigation after nail placement; irrigation, and debridement after nail removal following consolidation (all cases)
			Kostuik and Harrington (32)	Incision and drainage, intramedullary nail (4 cases)	50%	36 mo	None
			Cove et al. (12)	Serial debridements followed by external fixation (2 cases)	100%	7 mo	Autogenous bone grafting (all cases)
			Barquet et al. (33)	Serial debridements followed by external fixation (4 cases)	100%	9 mo	Cancellous bone grafting (all cases)
			Slätis and Paavolainen (34)	Debridement and external fixation (3 cases)	67%	5 mo	Cancellous bone grafting (all cases)
		External fixation	Ueng et al. (35)	Debridement followed by external fixation (5 cases)	100%	10 mo	Antibiotic-eluting beads for 2 to 6 wk and cancellous bone grafting (all cases)
		Traction and casting	Cove et al. (12)	Serial debridements followed by external fixation (5 cases)	80%	11 mo	Vascularized fibular transfer and autogenous bone grafting

							(all cases)
	Segmental defect	Intramedullary nail	Ueng et al. (13)	Augmentative plating over a retained intramedullary nail (7 cases) (13)	100%	7 mo	Cancellous bone grafting (all cases)
		Following debridement or traumatic bone loss	Jupiter et al. (36)	Vascularized fibular graft (7 cases)	71%	5 mo	None
			Muramatsu et al. (37)	Vascularized fibular graft (17 cases)	94%	8 mo	None
			Yajima et al. (38)	Vascularized fibular graft (20 cases)	75%	6 mo	Autogenous bone grafting (9 cases)
			Song et al. (39)	Vascularized fibular graft (17 cases)	60%	9 mo	Autogenous bone grafting at docking site (all cases)
			Wei et al. (40)	Vascularized fibular graft (10 cases)	50%	8 mo	None
			Wei et al. (40)	Vascularized fibular graft (7 cases)	100%	8 mo	None
			Hou and Liu (41)	Vascularized fibular strut graft (5 cases)	100%	7 mo	None
			Chapman (42)	Intramedullary nailing and closed intramedullary bone grafting (8 cases)	100%	Not reported	None
			Song et al. (39)	Bone transport (20 cases)	70%	10 mo	None
			Smrke and Arnez (43)	Bone transport (3 cases)	100%	34 mo	Free flap transfer (all cases)
			Jaffe et al. (44)	Bulk allograft (4 cases)	75%	6.7 mo	Fixation with dynamic compression plate (all cases)
Supracondylar	Uninfected	Intramedullary nail	Brinker and O'Connor (28)	SCONE (2 cases) (28)	100%	6 mo	None
		Plate and screw fixation	Bellabarba et al. (45)	Repeat plate and screw fixation (20 cases)	100%	4 mo	Bone graft substitute (1 case)
			Chapman and Finkemeier (46)	Repeat plate and screw fixation (16 cases)	94%	8 mo	Autogenous bone graft (15 cases) and bone-graft substitute (1 case)
			Wang and Weng (47)	Repeat plate and screw fixation (10 cases)	100%	5 mo	Cortical allograft struct grafts and corticocancellous autograft (all cases)
			Koval et al. (48)	Retrograde intramedullary nailing (16 cases)	25%	17 mo	Autogenous bone graft (13 cases)
			Kempf et al. (7)	Antegrade intramedullary nail	100%	4 mo	None

(Continued)

Table 1 Literature Review of Femoral Nonunions (*Continued*)

Anatomic location	Subgroup	Most recent failed treatment	Authors	Treatment (number of cases)	Success rate	Time to bony union	Adjunctive treatments
				(5 cases)			
			Ali and Saleh (49)	External fixation (10 cases)	100%	10 mo	None
			Haidukewych et al. (50)	Total knee arthroplasty (15 cases)	80%	Not applicable	None
			Freedman et al. (51)	Tumor replacement prosthesis (2 cases)	100%	Not applicable	None
	Infected	Plate and screw fixation	Ali and Saleh (49)	Debridement followed by external fixation (5 cases)	80%	11 mo	None
			Freedman et al. (51)	Tumor replacement prosthesis (1 case)	100%	Not applicable	None
		External fixator	Chapman and Finkemeier (46)	Plate and screw fixation (2 cases)	100%	14 mo	Autogenous bone graft (all cases)
	Periprosthetic		Anderson et al. (52)	Total knee arthroplasty, long femoral stem (6 cases)	83%	9 mo	None
Condylar (intra-articular)	No. of cases reported in the literature						

and two oblique views of the nonunion site itself on small cassette films for improved magnification and resolution; and (9) standing AP, 51 in alignment radiographs of both limbs to assess leg length discrepancies and deformities.

The current plain films are used to assess the following characteristics: (i) anatomic location, (ii) healing effort, (iii) bone quality, (iv) surface characteristics [(a) surface area of adjacent fragments, (b) extent of current bony contact, (c) orientation of fracture lines, and (d) stability to axial compression], (v) status of previously implanted hardware, and (vi) deformities [that should be characterized by location, magnitude, and direction and should include a description of the deformity in terms of i. length, ii. angulation, iii. rotation, and iv. translation (53–55)].

For femoral nonunions, the anatomic location is classified as subtrochanteric, diaphyseal, supracondylar, or condylar (i.e., when intra-articular involvement is present). Diaphyseal nonunions involve primarily cortical bone, whereas distal femoral metaphyseal nonunions largely involve cancellous bone.

The radiographic assessment of healing effort includes evaluating radiolucent lines and gaps and callus formation. The assessment of bone quality includes observing (i): sclerosis; (ii) atrophy; (iii) osteopenia; and (iv) bony defects.

COMPUTED TOMOGRAPHIC SCANNING AND TOMOGRAPHY

Assessment of bony healing in femoral nonunions may be difficult because overlying hardware may obstruct plain radiographs. In such cases, computed tomographic (CT) scans are particularly helpful in estimating the percentage of the cross-sectional area that shows bridging bone. The cross-sectional area of bridging bone may be followed on serial CT scans to evaluate the progression of fracture consolidation.

CT scans are also useful for assessing articular step off, joint incongruency, and bony healing in cases of intra-articular nonunions. Rotational deformities of the femur may be accurately quantified using CT by comparing the relative orientations of the proximal and distal segments of the involved bone to the contralateral normal bone (56–60).

NUCLEAR IMAGING

A variety of studies, when used in concert, are useful for assessing: (i) bone vascularity at the nonunion site, (ii) the presence of a synovial pseudarthrosis, and (iii) infection.

Technetium-99m-pyrophosphate (bone scan) complexes will show increased uptake in viable nonunions but decreased tracer uptake in nonviable nonunions. The diagnosis of synovial pseudarthrosis can be made by technetium-99m-pyrophosphate bone scanning, which will show a ''cold cleft'' at the nearthrosis between the hot ends of the ununited bone (61–64).

Radiolabeled white blood cell scans (such as with indium-111 or technetium-99m HMPAO) are useful tools for the evaluation of acute infections of bone. Gallium scans are AQ2
useful for the evaluation of chronic infections of bone. The combination of a gallium-67 citrate scan and a technetium-99m sulfa colloid bone marrow scan can clarify the diagnosis of chronic infection.

OTHER RADIOLOGIC STUDIES

Ultrasonography is useful for assessing the status of the bony regenerate (distraction osteogenesis) during bony transport or lengthening. Ultrasonography is also useful for confirming the presence of a fluid-filled pseudocapsule in cases of suspected synovial pseudarthrosis by nuclear medicine study.

Magnetic resonance imaging may be used to evaluate the soft tissues at the nonunion site or the cartilaginous and ligamentous structures of the adjacent joints. Sinograms may be used to image the course of a sinus tract in cases of infected nonunions. Angiography provides anatomic detail regarding the status of vessels as they course through a scarred and deformed limb. This study is unnecessary for most patients who have a femoral nonunion, unless there is concern regarding the viability of the limb.

Table 2 Clinical Management of Subtrochanteric Femoral Nonunions

Subgroup	Most recent failed treatment	Treatment options	Pearls	Surgical technique
Uninfected	Intramedullary nail	Plate and screw fixation with intramedullary and extramedullary autogenous iliac crest bone graft	An oblique osteotomy may be necessary in order to improve surface characteristics and to facilitate interfragmentary lag screw fixation Autologous iliac crest bone graft is delivered to the nonunion site via a chest tube placed into the medullary canal, as described by Chapman (42) Consider the use of BMPs (66,67) Proximal femoral locking plates increase construct rigidity	
	Plate and screw fixation	Repeat plate and screw fixation with intramedullary and extramedullary autogenous iliac crest bone graft; interfragmentary lag screw fixation	An oblique osteotomy may be necessary in order to improve surface characteristics and to facilitate interfragmentary lag screw fixation Consider the use of BMPs (66,67)	
Infected	Intramedullary nail	Nail removal and serial debridements followed by plate and screw fixation with intramedullary and extramedullary autogenous iliac crest bone graft	Autologous iliac crest bone graft is delivered to the nonunion site via a chest tube placed into the medullary canal, as described by Chapman (42) Place an intramedullary antibiotic-eluting nail at the time of each debridement	The antibiotic-eluting nail is constructed by using a chest tube as a mold and placing liquid PMMA with antibiotic powder inside the chest tube with a wire as a central core

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	Plate and screw fixation	Hardware removal and serial debridements followed by repeat plate and screw fixation with intramedullary and extramedullary autogenous iliac crest bone graft	An oblique osteotomy may be necessary in order to improve surface characteristics and to facilitate interfragmentary lag screw fixation	
Segmental defect	Intramedullary nail	Defect <4 cm: plate and screw fixation with autogenous iliac crest bone graft	Consider acute shortening with immediate bone-to-bone contact with the plan of restoring length later in a staged procedure (trim the nonunion site in order to improve surface characteristics); an oblique osteotomy may be necessary in order to facilitate interfragmentary lag screw fixation Consider the use of BMPs (66,67)	
		Defect >4 cm: Ilizarov bone transport or intercalary bulk allograft over an intramedullary nail	Consider bone transport over an intramedullary nail	Proximal femoral half-pin fixation anterior or posterior to the nail is facilitated by a "miss-a-nail" targeting device
	Plate and screw fixation	Defect <4 cm: repeat plate and screw fixation with autogenous iliac crest bone graft	Consider acute shortening with immediate bone-to-bone contact with the plan of restoring length later in a staged procedure (trim the nonunion site in order to improve surface characteristics); an oblique osteotomy may be necessary in order to facilitate interfragmentary lag screw fixation Consider the use of BMPs (66,67)	
		Defect >4 cm: Ilizarov bone transport or intercalary bulk allograft over an intramedullary nail	Consider bone transport over an intramedullary nail	Proximal femoral half-pin fixation anterior or posterior to the nail is facilitated by a "miss-a-nail" targeting device

Table 3 Clinical Management of Diaphyseal Femoral Nonunions

Subgroup	Most recent failed treatment	Treatment options	Pearls	Surgical technique
Uninfected	Intramedullary nail	Exchange nailing	The new nail should be a minimum of 2 mm to 3 mm larger than the nail being exchanged Custom nails may be needed for patients who have large nails in situ or large femoral medullary canals	
		Consider nail dynamization for axially stable nonunions that are 3 to 4 mo out from surgical treatment		
	Plate and screw fixation	Repeat plate and screw fixation with autogenous iliac crest bone graft	An oblique osteotomy may be necessary in order to facilitate interfragmentary lag screw fixation Consider dual plating Large fragment locking plates increase construct rigidity Consider the use of BMPs (66,67)	
	External fixator	Compression/distraction with the external fixator, if the fixator allows or exchange for an Ilizarov external fixator or external fixator removal with plate and screw fixation with autogenous iliac crest bone graft		
			An oblique osteotomy may be necessary in order to facilitate interfragmentary lag screw fixation Consider dual plating Consider the use of BMPs (66,67) Large fragment locking plates increase construct rigidity	
Infected	Intramedullary nail	Nail removal and serial debridements via intramedullary reaming followed by exchange nailing	Consider autologous iliac crest bone graft delivered to the nonunion site via a chest tube placed into the medullary canal, as described by Chapman (42)	The antibiotic-eluting nail is constructed by using a chest tube as a mold and placing liquid PMMA with antibiotic powder inside the chest tube with a wire as a central core
			Place an intramedullary antibiotic-eluting nail at the time of each debridement	

	Plate and screw fixation	Hardware removal and serial debridements followed by repeat plate and screw fixation with autogenous iliac crest bone graft or Ilizarov compression–distraction	An oblique osteotomy may be necessary in order to facilitate interfragmentary lag screw fixation Consider dual plating Large fragment locking plates increase construct rigidity	
	External fixator	Serial debridement followed by Ilizarov compression–distraction or bone transport or external fixator removal and serial debridements followed by plate and screw fixation with autogenous iliac crest bone graft		
Segmental defect	Intramedullary nail	Defect <4 cm: Plate and screw fixation with autogenous iliac crest bone graft	Consider dual plating Consider the use of BMPs (66,67) Consider acute shortening with immediate bone-to-bone contact with the plan of restoring length later in a staged procedure (trim the nonunion site in order to improve surface characteristics); an oblique osteotomy may be necessary in order to facilitate interfragmentary lag screw fixation	
		Defect >4 cm: Ilizarov bone transport or intercalary bulk allograft over an intramedullary nail or vascularized fibular graft	Consider bone transport over an intramedullary nail	Nonunions proximal to the midshaft are most commonly treated with bone transport over an antegrade nail (femoral half-pin fixation anterior or posterior to the nail is facilitated by a "miss-a-nail" targeting device) Nonunions distal to the midshaft are most commonly treated with bone transport over a retrograde nail
	Plate and screw fixation	Defect <4 cm: Repeat plate and screw fixation with autogenous iliac crest bone graft	Consider dual plating Consider the use of BMPs (66,67) Consider acute shortening with immediate bone-to-bone contact with the plan of restoring length later in a staged procedure (trim the nonunion site in order to improve surface characteristics); an oblique osteotomy may be necessary in order to facilitate interfragmentary lag screw fixation	

(*Continued*)

Table 3 Clinical Management of Diaphyseal Femoral Nonunions (*Continued*)

Subgroup	Most recent failed treatment	Treatment options	Pearls	Surgical technique
		Defect >4 cm: Ilizarov bone transport or Intercalary bulk allograft over an intramedullary nail or vascularized fibular graft	Consider bone transport over an intramedullary nail	Nonunions proximal to the midshaft are most commonly treated with bone transport over an antegrade nail (femoral half-pin fixation anterior or posterior to the nail is facilitated by a "miss-a-nail" targeting device) Nonunions distal to the midshaft are most commonly treated with bone transport over a retrograde nail
	External fixator	Defect <4 cm: Plate and screw fixation with autogenous iliac crest bone graft or Ilizarov compression–distraction or Ilizarov bone transport	Consider dual plating	
			Consider the use of BMPs (66,67)	
			Consider acute shortening with immediate bone-to-bone contact with the plan of restoring length later in a staged procedure (trim the nonunion site in order to improve surface characteristics); an oblique osteotomy may be necessary in order to facilitate interfragmentary lag screw fixation	

	Defect >4 cm: Ilizarov bone transport or intercalary bulk allograft over an intramedullary nail or vascularized fibular graft	The technique of bone transport over an intramedullary nail is useful for cases with large segmental defects; however, the risk of deep infection is increased in patients who have had previous external fixation (4,68). In general, the risk is highest in patients whose prior external fixation was recently removed and was in situ for an extended period. The risks and benefits of conventional transport versus transport over a nail in patients with prior external fixation must be weighed by the treating surgeon on a case-by-case basis	Nonunions proximal to the midshaft are most commonly treated with bone transport over an antegrade nail (femoral half-pin fixation anterior or posterior to the nail is facilitated by a "miss-a-nail" targeting device) Nonunions distal to the midshaft are most commonly treated with bone transport over a retrograde nail
Periprosthetic	Revision arthroplasty with a long-stem femoral component or plate and screw fixation with autogenous iliac crest bone graft or both revision arthroplasty with a long-stem femoral component and plate and screw fixation with autogenous iliac crest bone graft	Revision arthroplasty is most appropriate for loose prostheses or those readily amenable to revision Consider dual plating Consider the use of BMPs (66,67) Large fragment locking plates increase construct rigidity and allow for unicortical screw placement in areas where the femoral prosthesis occupies the medullary canal Consider the use of strut cortical allograft with cable fixation to augment stability Specialized periprosthetic cable-plate systems may be advantageous in certain cases	

Venous Doppler studies should be performed preoperatively to rule out a deep venous thrombosis in patients with a lower extremity nonunion who have been confined to a wheelchair or bedridden for an extended period.

LABORATORY STUDIES

In addition to routine lab work, the sedimentation rate and C-reactive protein are useful for following the course of infection. In cases of suspected infection, the nonunion site may be aspirated or biopsied and the material sent for a cell count and Gram stain, and cultured for aerobic, anaerobic, fungal, and acid-fast bacillus organisms. In order to encourage the highest yield possible, all antibiotics should be discontinued at least one week prior to aspiration.

CLASSIFICATION

Nonunions of the femoral shaft and distal femur can be classified according to anatomic location, the presence or absence of infection or a segmental defect, the most recent failed surgical treatment method, and nonunion type (4).

Weber and Cech (65) have classified nonunions based on radiographic healing effort and bone quality into two categories:

1. Viable nonunions—those capable of biological activity, and
2. Nonviable nonunions—those incapable of biological activity.

Viable nonunions include hypertrophic nonunions and oligotrophic nonunions. Hypertrophic nonunions possess adequate vascularity and display callus formation. They arise because of inadequate mechanical stability with persistent motion at the fracture surfaces. Oligotrophic nonunions possess an adequate blood supply but little or no callus formation. Oligotrophic nonunions arise secondary to inadequate reduction with displacement at the fracture site.

An atrophic nonunion is the most advanced type of nonviable nonunion. Atrophic nonunions do not display callus formation and a radiolucent gap is observable on plain radiographs. This gap is bridged with fibrous tissue that has no osteogenic capacity. The ends of the bony surfaces are avascular and usually appear partially absorbed and osteopenic.

Anatomic location is divided into four regions: subtrochanteric, diaphyseal, supracondylar, and condylar (intra-articular).

TREATMENT OPTIONS AND SURGICAL TECHNIQUES

An overview of treatment options and surgical techniques is given in Tables 2 through 5. In cases of infected nonunion, the initial treatment is aimed at eliminating infection regardless of the anatomic location and most recent failed treatment. After elimination of infection, treatment can then proceed. T2 – T5

SUBTROCHANTERIC FEMORAL NONUNIONS

The incidence of subtrochanteric femoral nonunions due to failure of internal fixation (intramedullary nail or plate and screw fixation) has been reported to range from 0% to 12% (69,70). Regardless of the most recent failed treatment, plate and screw fixation (or repeat plate and screw fixation) with bone grafting is the most common technique that we employ (Fig. 1), F1
unless there is a large segmental defect (>4 cm). Repeat plate and screw fixation with autogenous cancellous bone grafting or allografting has been reported to have high union rates in the treatment of subtrochanteric nonunions (5).

Reamed intramedullary nailing with or without bone grafting has also been reported to be successful in subtrochanteric nonunions that are amenable to nailing (5–7). A defect in this region larger than 4 cm may require Ilizarov bone transport or an intercalary bulk allograft over an intramedullary nail to restore bony continuity (71).

Table 4 Clinical Management of Supracondylar Femoral Nonunions

Subgroup	Most recent failed treatment	Treatment options	Pearls	Surgical technique
Uninfected	Intramedullary nail	SCONE (28) or plate and screw fixation with autogenous iliac crest bone graft	An oblique osteotomy may be necessary in order to improve surface characteristics and to facilitate interfragmentary lag screw fixation Specialized supracondylar locking plates increase construct rigidity	A retrograde nail facilitates proximal femoral half-pin placement because the nail does not occupy the most proximal portion of the femur
	Plate and screw fixation	Repeat plate and screw fixation with autogenous iliac crest bone graft	Consider dual plating Specialized supracondylar locking plates increase construct rigidity	
	External fixator	Ilizarov compression–distraction or plate and screw fixation with autogenous iliac crest bone graft		
Infected	Intramedullary nail	Nail removal and serial debridements via intramedullary reaming followed by plate and screw fixation with autogenous iliac crest bone graft or Ilizarov compression–distraction or serial debridements followed by bony resection through or proximal to the nonunion and reconstruction with a tumor replacement prosthesis	Consider autologous iliac crest bone graft delivered to the nonunion site via a chest tube placed into the medullary canal, as described by Chapman (42) Place an intramedullary antibiotic-eluting nail at the time of each debridement	The antibiotic-eluting nail is constructed by using a chest tube as a mold and placing liquid PMMA with antibiotic powder inside the chest tube with a wire as a central core
	Plate and screw fixation	Hardware removal and serial debridements followed by repeat plate and screw fixation with autogenous iliac crest bone graft or Ilizarov compression–distraction or Serial debridements followed by bony resection through or proximal to the nonunion and reconstruction with a tumor replacement prosthesis	An oblique osteotomy may be necessary in order to improve surface characteristics and to facilitate interfragmentary lag screw fixation Consider dual plating	
	External fixator	Serial debridements followed by Ilizarov compression/distraction or bone transport or external fixator removal and serial debridements followed by plate and screw fixation with autogenous iliac crest bone graft or external		

(*Continued*)

Table 4 Clinical Management of Supracondylar Femoral Nonunions (*Continued*)

Subgroup	Most recent failed treatment	Treatment options	Pearls	Surgical technique
		fixator removal and serial debridements followed by bony resection through or proximal to the nonunion site and reconstruction with a tumor replacement prosthesis		
Segmental defect	Intramedullary nail	Defect <4 cm: plate and screw fixation with autogenous iliac crest bone graft or bony resection through or proximal to the nonunion site and reconstruction with a tumor replacement prosthesis	Consider acute shortening with immediate bone-to-bone contact with the plan of restoring length later in a staged procedure	
		Defect >4 cm: Ilizarov bone transport or bony resection through or proximal to the nonunion site and reconstruction with a tumor replacement prosthesis or intercalary bulk allograft over an intramedullary nail	Consider bone transport over an intramedullary nail	
Segmental defect	Plate and screw fixation	Defect <4 cm: repeat plate and screw fixation with autogenous iliac crest bone graft or bony resection through or proximal to the nonunion site and reconstruction with a tumor replacement prosthesis	Consider acute shortening with immediate bone-to-bone contact with the plan of restoring length later in a staged procedure	
		Defect >4 cm: Ilizarov bone transport or bony resection through or proximal to the nonunion site and reconstruction with a tumor replacement prosthesis or intercalary bulk allograft over an intramedullary nail	Consider bone transport over a retrograde intramedullary nail	A retrograde nail facilitates proximal femoral half-pin placement because the nail does not occupy the most proximal portion of the femur

	External fixator	Defect <4 cm: plate and screw fixation with autogenous iliac crest bone graft or Ilizarov compression–distraction or Ilizarov bone transport or bony resection through or proximal to the nonunion site and reconstruction with a tumor replacement prosthesis Defect >4 cm: Ilizarov bone transport or bony resection through or proximal to the nonunion site and reconstruction with a tumor replacement prosthesis or intercalary bulk allograft over an intramedullary nail	Consider acute shortening with immediate bone-to-bone contact with the plan of restoring length later in a staged procedure
Periprosthetic		Revision arthroplasty with a long-stem femoral component or plate and screw fixation with autogenous iliac crest bone graft or retrograde femoral nailing with autogenous iliac crest bone graft or both revision arthroplasty and fixation with plate and screw fixation or retrograde intramedullary nail fixation with autogenous iliac crest bone graft	Revision arthroplasty is most appropriate for loose prostheses or those readily amenable to revision Consider dual plating Consider the use of BMPs (66,67) Large fragment locking plates increase construct rigidity and allow for unicortical screw placement in areas where the femoral prosthesis occupies the medullary canal Consider the use of strut cortical allograft with cable fixation to augment stability Specialized periprosthetic cable-plate systems may be advantageous in certain cases

Table 5 Clinical Management of Condylar (Intra-articular) Femoral Nonunions

Subgroup	Most recent failed treatment	Treatment options	Technique pearls
Uninfected	Intramedullary nail	Interfragmentary lag screw fixation or knee replacement arthroplasty	Knee replacement arthroplasty is most appropriate in older adults or those whose nonunions have failed to unite despite multiple surgical attempts
	Plate and screw fixation	Repeat plate and screw fixation or knee replacement arthroplasty	Knee replacement arthroplasty is most appropriate in older adults or those whose nonunions have failed to unite despite multiple surgical attempts
Infected	Intramedullary nail	Serial debridements followed by knee replacement arthroplasty, osteoarticular allograft reconstruction, or knee arthrodesis	An antibiotic-eluting spacer may be useful following debridement but prior to reconstruction
	Plate and screw fixation	Serial debridements followed by knee replacement arthroplasty, osteoarticular allograft reconstruction, or knee arthrodesis	An antibiotic-eluting spacer may be useful following debridement but prior to reconstruction

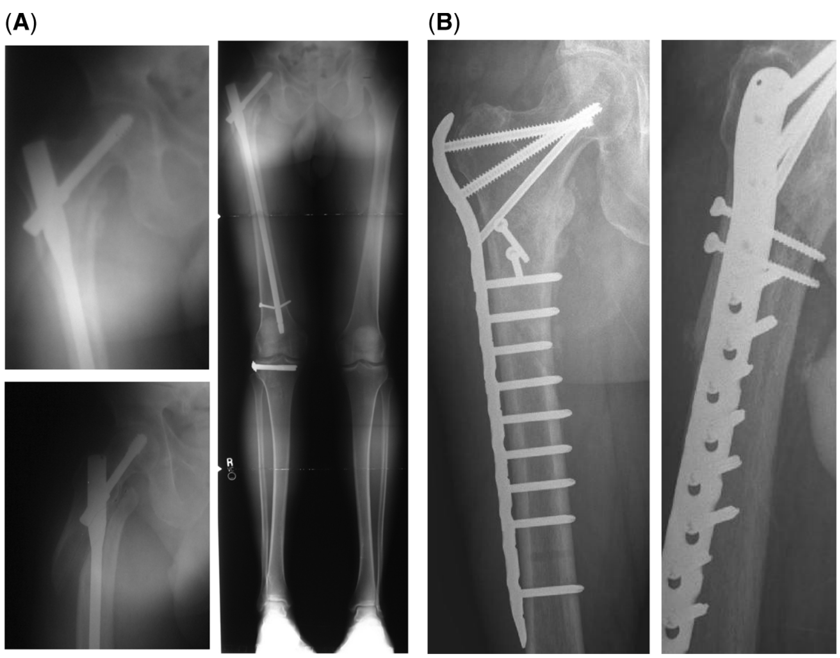

Figure 1 (**A**) Presenting anteroposterior (AP) and lateral radiographs of a 51-year-old man referred in four months following intramedullary nail fixation of a reverse obliquity intertrochanteric/subtrochanteric femur fracture. The lateral view shows poor bone-to-bone contact with no evidence of progression to healing whatsoever. This patient complained of increasing pain and a sensation of abnormal motion in thigh. (**B**) Follow-up AP and lateral radiographs five months following reconstruction with open reduction, interfragmentary lag screw fixation, fixation with a proximal femoral locking plate (Synthese, Paoli, Pennsylvania), and intramedullary and extramedullary autogenous bone grafting. At follow-up, the nonunion site is solidly healed and the patient has returned to preinjury function without any symptoms.

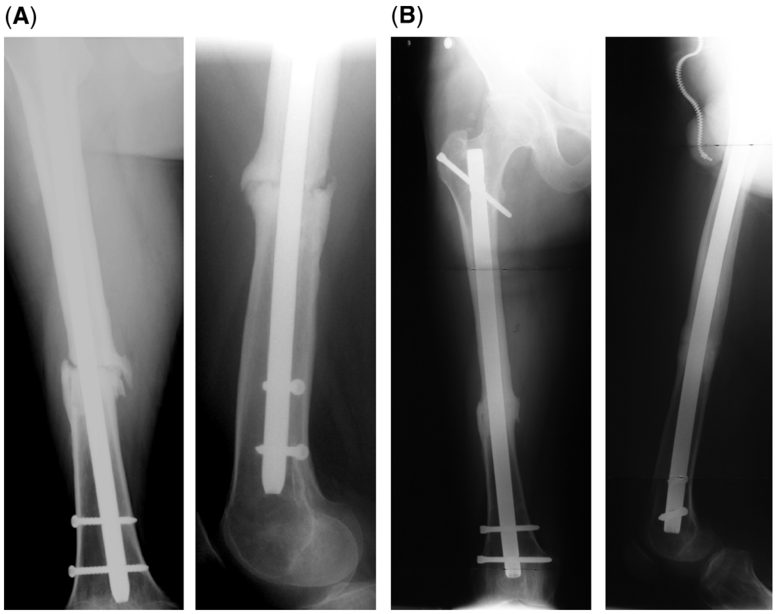

Figure 2 (**A**) Presenting anteroposterior (AP) and lateral radiographs of a 33-year-old man referred in for a diaphyseal nonunion 11 months following intramedullary nail fixation. (**B**) Follow-up AP and lateral radiographs seven months following exchange nailing show solid bony union.

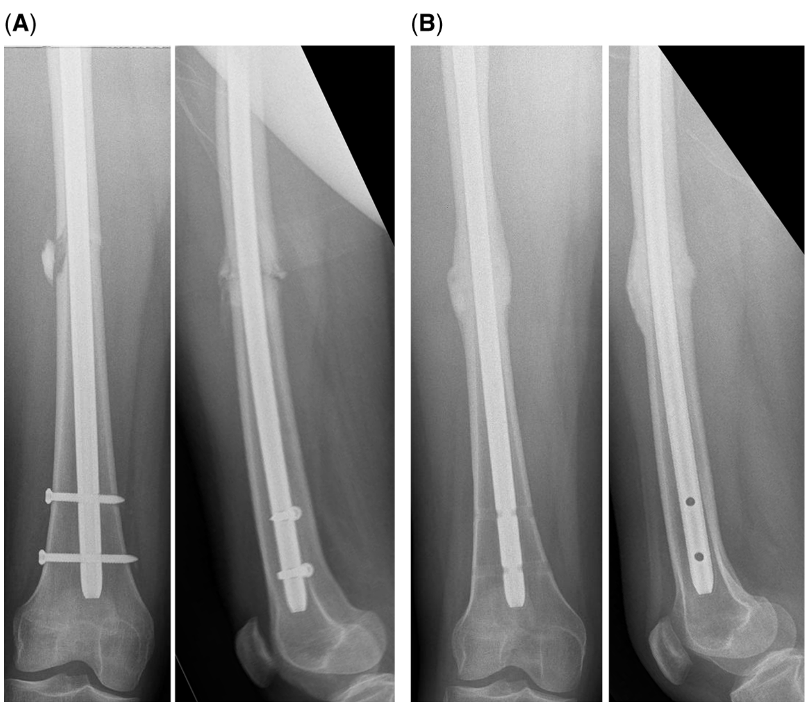

Figure 3 (**A**) Presenting anteroposterior (AP) and lateral radiographs of a 17-year-old girl with cerebral palsy referred in 3.5 months following intramedullary nail fixation of a femoral shaft fracture. The patient complained of progressively worsening pain in right thigh. (**B**) Follow-up AP and lateral radiographs five months following nail dynamization show solid union. At follow-up, the patient is asymptomatic and has returned to preinjury functional status.

DIAPHYSEAL FEMORAL NONUNIONS

The incidence of diaphyseal femoral nonunions following intramedullary nailing of an acute fracture has been reported to range from 2% to 13%; the highest nonunion rates are associated with unreamed nailing (15,72).

Patients with diaphyseal femoral nonunions who have failed intramedullary nailing generally receive exchange nailing (Fig. 2) or nail dynamization when they are three to four months F2 out from surgical treatment and the nonunion is axially stable (Fig. 3) (7,12,15–23,25,26,29,31). F3 Patients who have failed one or more exchange nailings may require slow compression over a nail using external fixation (SCONE) (Fig. 4) (28). Augmentative plating over the nail has also F4 been reported to be successful, although this technique requires exposure of the nonunion site and has a slightly longer healing period (13,14). Alternatively, the nail can be removed and the nonunion site can be stabilized using plate and screw fixation (8–12). Autogenous bone grafting around a previously placed nail without providing augmentative stabilization has had mixed results and we do not recommend this technique (10,15). Infected diaphyseal nonunions may require external fixation after debridement to provide stability or address segmental defects (12,33,34).

Failed plate and screw fixation usually responds well to repeat plate and screw fixation with bone grafting (9,12), but may require treatment with Ilizarov external fixation if infection or a segmental defect is present (73). Reamed intramedullary nailing with or without bone grafting following failed plate and screw fixation has been reported to have a very high success rate (7,9,10,17,18,21,23,29–32); this is not a strategy that we often employ.

Patients with failed external fixation may require plate and screw fixation and bone grafting after removal of the fixator, a change in the treatment mode of the fixator (for example, from static to compression–distraction), or conversion to Ilizarov external fixation (compression–distraction or bone transport).

In the event of a segmental defect larger than 4 cm, Ilizarov bone transport may be the method of choice regardless of the most recent failed treatment (39,43). Vascularized fibular grafts, either single or double, can also be successful in the treatment of large segmental defects, but are associated with vascular complications and are at significant risk for subsequent fracture (36–40). Intercalary allograft over an intramedullary nail is also a useful treatment option (4,44).

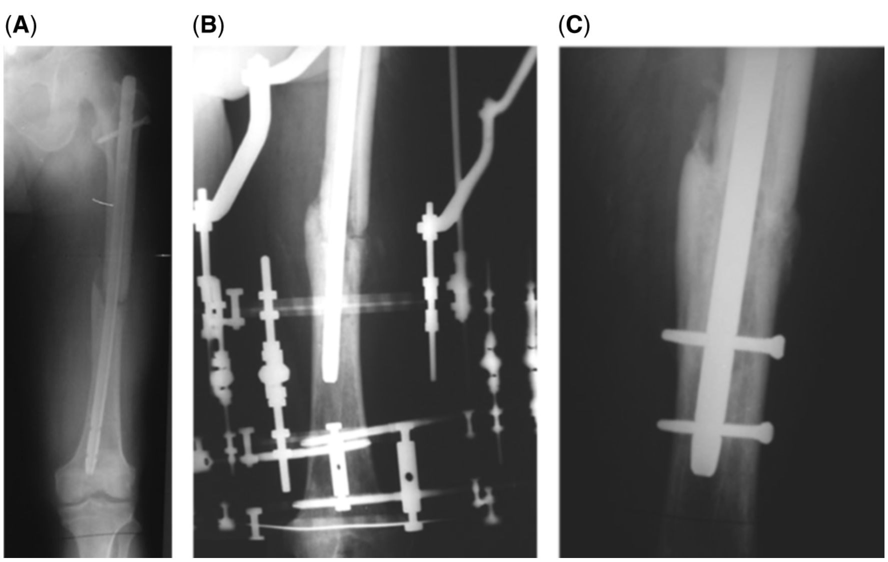

Figure 4 (**A**) Presenting anteroposterior (AP) radiograph of a 67-year-old man referred in 30 months following an open femoral shaft fracture and seven previous surgeries, including two previous exchange nailings and bone grafting. (**B**) AP radiograph on postoperative day 75 showing slow compression over a nail using external fixation (SCONE). (**C**) Follow-up AP radiograph four months following SCONE shows solid bony union.

Figure 5 (**A**) Presenting anteroposterior (AP) and lateral radiographs of a 50-year-old woman referred in nine months following exchange retrograde nailing of a supracondylar nonunion. A frank nonunion with hardware failure and deformity is present. (**B**) AP radiograph 10 months following open reduction internal fixation and autogenous bone grafting reveals solid bony union. (**C**) Later follow-up following symptomatic hardware removal shows solid bridging bone on AP and lateral views.

Periprosthetic diaphyseal nonunions may require revision arthroplasty, plate and screw fixation with bone grafting, or both.

SUPRACONDYLAR FEMORAL NONUNIONS

The incidence of supracondylar femoral nonunions has been reported to range from 3% to 6% when treated with a supracondylar intramedullary nailing system (74–76), and from 0% to 13% with plate and screw fixation (77–80). Intramedullary nailing following failure of plate and screw fixation is a poor treatment option for supracondylar nonunions. Koval et al.

reported a 75% failure rate for distal femoral nonunions treated with retrograde intramedullary nailing (48). In contrast, Kempf et al. reported good success using a dynamically locked antegrade intramedullary nail in five cases (7).

Supracondylar nonunions that have most recently failed intramedullary nailing are treated at our institution by SCONE (28). Other options include Ilizarov compression–distraction, external fixation (49), and plate and screw fixation with bone graft (Fig. 5) (11,46,47). Older patients or patients with limited physical demands may benefit from total knee arthroplasty using a long femoral stem, a megaprosthesis, a tumor replacement prosthesis, or an allograft–prosthesis composite (50,51,81).

Patients who have most recently failed external fixation are treated by Ilizarov compression–distraction or bone transport, or plate and screw fixation with bone grafting. Ilizarov bone transport or intercalary bulk allograft over an intramedullary nail are used to treat segmental defects larger than 4 cm. Cases of infected supracondylar nonunion or nonunion associated with a large segmental defect may require bony resection proximal to the nonunion site and reconstruction using a tumor prosthesis.

Periprosthetic supracondylar nonunions may be treated by revision arthroplasty with a long-stem femoral component, plate and screw fixation or retrograde femoral nailing with autogenous iliac crest bone graft, or a combination of these techniques.

CONDYLAR (INTRA-ARTICULAR) FEMORAL NONUNIONS

The incidence of condylar femoral nonunions has been reported to range from 1% to 13% (82,83). These cases may be successfully treated to union with interfragmentary lag screw fixation (Fig. 6). In older adults or patients who have failed multiple surgical attempts, knee replacement arthroplasty may be appropriate. In cases with infection, an osteoarticular allograft or knee arthrodesis may be alternatives to knee replacement arthroplasty. Following serial debridement, an antibiotic spacer may be used to decrease the chance of reinfection following the later reconstruction.

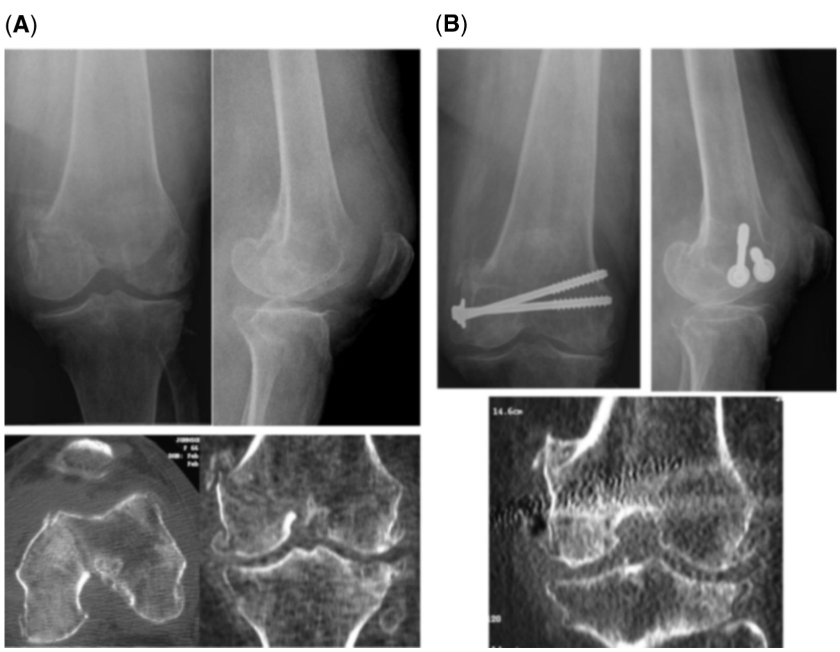

Figure 6 (**A**) Presenting anteroposterior (AP) and lateral radiographs and computed tomographic (CT) scan of a 81-year-old woman referred in 4.5 months following a fall at home. Radiographs and CT scan reveal a nonunion of the medial femoral condyle. (**B**) Follow-up AP and lateral radiographs and CT scan three months following interfragmentary lag screw fixation show solid bony union.

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